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A technical review on use of liquid-desiccant dehumidification for air-conditioning application

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Abstract

Liquid-desiccant dehumidification has been proved to be an effective method to extract the moisture of air with relatively less energy consumption, especially compared with conventional vapour compression system. To date, the conventional dehumidification mode with desiccant solution has been improved or replaced by newly emerged energy-saving systems with better performance. This paper gives a detailed account of the general features of the major desiccant dehumidification techniques and configurations of the related systems; meanwhile, attention has been paid to both technological and theoretical development of regenerator, which is an indispensable component of the liquid-desiccant dehumidification system. Moreover, a summary of the experimental and analytical studies to optimize the system performance has been made. Some new hybrid systems that greatly expand the desiccant dehumidification technique in industrial and residential applications, as well as effectively promoting the single system's performance, are also introduced. Finally, future study and application for liquid-desiccant dehumidification techniques are concluded.

Keywords: Liquid desiccant; Dehumidification; Regenerator; Performance; Hybrid systems

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1. Introduction

As energy shortage emerges as an issue of growing concern in the world, coupled with the threat to environment posed by the conventional refrigerants, the need to come up with the new-fangled energy-saving as well as environmental-friendly air-conditioning systems has been more urgent than ever before. The liquid-desiccant dehumidification systems driven by low-grade heat sources can satisfactorily meet those needs; meanwhile, they provide an ideal area for the application of waste heat discharged from local factories, and the employment of brine solution as absorbent brings no damage to environment. The earliest liquid-desiccant system was suggested and experimentally tested by Löf [1] using triethylene glycol as the desiccant.

Desiccant dehumidification has long been adopted for both industrial and agricultural purposes, such as humidity control in textile mill and post harvest low-temperature crop-drying in stores, and is now taking a more and more prominent role in the air-conditioning field. Its economical and effective humidity control at low and moderate temperature really dwarfs the conventional method of humidity control, which is generally by lowering the air temperature to around the dry bulb temperature. As a result, the dehumidified air by such an approach is cooler than that required indoor comfort level, which in turn causes the reheat of energy loss. Meanwhile, the condensed water provides a breeding ground for indoor bacteria. Desiccant dehumidification avoided the above problems in handling the humidity of process air, since it makes full use of surface vapour pressure difference to realize moisture transfer between the process air and the liquid desiccant.

Nomenclature

c	salt concentration of desiccant solution (kg/kg)
d	air humidity ratio (g/kg)
m	mass flow rate (kg/s)
p	partial vapour pressure (kPa)
S	storage capacity for dehumidification enthalpy (MJ/m^3)
t	temperature (°C)
V	volume (m^3)
r	latent heat (kJ/kg)

Greek symbol

ε_{de}	efficiency of dehumidifier
ε_{re}	efficiency of regenerator
ρ	density (kg/m^3)
η	dimensionless temperature ratio

Subscript

a	process air
equ	equilibrium
in	inlet of labelled flow
max	maximum
out	outlet of labelled flow
s	desiccant solution
sat	saturation

2. Principles and features of the liquid-desiccant dehumidification

Fig. 1 presents the schematic diagram of a basic liquid-desiccant dehumidification and air-conditioning system, which are generally made of four major units, namely, dehumidification unit, regeneration unit, liquid-desiccant storage unit, and sensible heat handling unit. The task of dehumidification unit is to remove the moisture of the inlet air by bringing into contact with sprinkled liquid desiccant. The regeneration unit is used to regenerate the diluted solution flowing from dehumidification unit to an acceptable concentration (near the desiccant's initial concentration); thus, the continual operation of the cycle can be maintained. The liquid storage unit is aiming at realizing energy storage by storing strong solution. The sensible heat handling unit is to remove the sensible heat load of the process air flowing from the dehumidification unit according to indoor air comfort standards. The other such systems can be made through different arrangements, replacements and additions of components based on this system.

It is obvious that the configuration of the dehumidification unit is similar to that of refrigeration unit, expect that the former has an additional insulating layer and a filter layer, which are used separately to prevent environmental heat effect on dehumidification

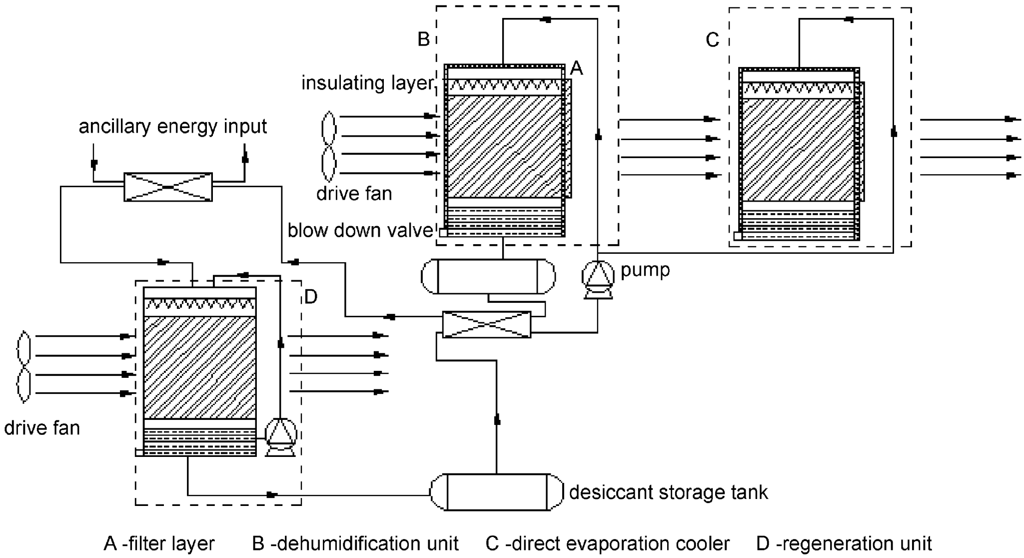

Fig. 1. Schematic diagram of liquid-desiccant dehumidification air-conditioning system.

and remove the droplet of the liquid desiccant brought by the process air. Both units adopt the same packing materials, but the processes are totally opposite. In the refrigeration unit, the surface vapour of diluted hot liquid desiccant is higher than that of inlet ambient air, so the direction of mass (water) transfer is from sprayed liquid film to process air; the weak solution is concentrated near to the initial concentration of the desiccant solution pumped into the dehumidifier. The surface vapour pressure difference between liquid-desiccant film and air is acting as the driving force for mass transfer; therefore, the diluted solution flowing from dehumidification unit need preheating to increase its surface vapour pressure to improve refrigeration efficiency. Low-grade energy hereby serves as the preheating source for weak desiccant as well as the driving force for the whole system. The ancillary heat exchanger here is necessary lest the low-grade energy is weak or unavailable. Similarly, the inlet liquid desiccant needs to be pre-cooled to lower its surface vapour pressure, thus better dehumidification efficiency can be achieved. The heat exchanger between the weak solution flowing out of the dehumidification unit and strong solution flowing in it can effectively preheat the former and pre-cool the latter. Besides, in order to maintain the low surface pressure of the desiccant solution, methods such as adding insulating layer to prevent the increase of solution temperature caused by heat transfer are taken to maintain the ideal mass transfer driving force. The desiccant storage tank is used for purpose of energy storage by storing the regenerated strong solution. It should be mentioned here that the storage tank is usually equipped with an ancillary heater to avoid crystallization, which will affect the normal operation of the system by clogging the pipe. It is self-evident that the main energy consumption occurs in the process of regeneration, which can be completed by low-grade energy, thus the application of attractive but not readily available low-temperature heat resources is greatly expanded. Additionally, their potential is enhanced by the energy storage.

The comparison between liquid-desiccant dehumidification system and conventional central air-conditioning systems is listed in Table 1 [46,47], and CACS stands for

Table 1
Comparison between liquid-desiccant dehumidification system and conventional central air-conditioning systems

System initial investment	Similar	
	CACS	LDDS
Operation cost	High	Save around 40% of cost
Driving energy source	Electricity, natural gas, vapour	Low-grade energy
Control over humidity	Average	Accurate
Indoor air quality	Average	Good
System instalment	Average	Slightly complicate
Energy storage capacity	Bad	Good

central air-conditioning system, while LDDS stands for liquid-desiccant dehumidification system.

3. Desiccants and packing materials

3.1. Liquid desiccants

The selection of the liquid desiccant is decisive in the overall performance of the dehumidification system, and will exert an immediate influence on the mass of dehumidification. Its selection depends on various operating parameters, such as boiling point elevation, energy storage density, regeneration temperature, thermo-physical properties, availability, cost, etc. Among the above parameters, the surface vapour pressure is one of major concern and has been investigated extensively and thoroughly. Lithium bromide, lithium chloride, triethylene glycol are among the most widely used single desiccants, their surface vapour pressure at low temperature and high concentration are lower than that of the humid process air. Attempts have been made by many researchers (such as Patil [2], Ahmed [3], Uemura [4], etc.) to provide the thermodynamic properties of the single desiccants.

Investigations and experiments found that calcium chloride is the cheapest and most readily available desiccant, but its vapour pressure at a given temperature is relatively high, and its unstable conditions depending on inlet air conditions and desiccant concentration in solution limit its widespread use.

Lithium chloride is the most stable desiccant with advantageously low vapour pressure, but its cost is slightly higher compared with others. The cost and vapour pressure of lithium bromide are intermediate. Triethylene glycol is the earliest used desiccant in liquid-desiccant dehumidification systems, but the liquid residence caused by its high viscosity make the system operation unstable. Besides, triethylene glycol has a very low surface vapour pressure, which causes some of them to evaporate into the air flowing into the conditioned areas. Owing to the difference of the purity of the metal-salt, the surface vapour pressure of the liquid desiccants often varies. Experimental measurement is an important method but not a universal method due to the capital support. Lithium chloride and calcium chloride are the universal desiccants mostly used to get cost-effective mixture in different weight combinations in the open literature. Conde [5] has developed formulations for the thermal properties of lithium and calcium chlorides. Sun et al. [6]

calculated and analysed the vapour pressure of the liquid desiccants based on classic thermodynamic principles. McNeely [7] provided thermodynamic properties of aqueous solution of lithium bromide. Kaita [8] developed an equation for thermodynamic properties of lithium bromide–water solutions at high temperatures, which are valid from concentrations of 40–65 wt% and also from temperatures of 40–210 °C. Morillon et al. [9] offered the water vapour pressure above saturated salt solutions at low temperatures, etc. Ertas and Kiris [10] gave the properties of lithium chloride (with the purity rate of 99.3%) and calcium chloride (with the purity rate of 90%) mixture, studies were conducted in the temperature range from 26.6 to 65.5 °C, investigation found that the mixture has low viscosity and is highly soluble over a considerable temperature range, and owns lower surface vapour pressure compared with the pure calcium chloride solution, the saving is about 30% compared with the pure lithium chloride solution with the same surface vapour pressure in the temperature range (20–30 °C).

Many researchers put their attention to the fashioning of mixed desiccant with lower surface vapour pressure and cost. Younus Ahmed et al. [11] used the simple mixed rules to predict the thermodynamic properties of liquid desiccant, and found that interaction parameter need not to be included in calculating the density and vapour pressure of the mixture, but must be included in predicting the viscosity. de Lucas et al. [12] provided the thermodynamic properties of the (water + lithium bromide + potassium acetate) system and (water + lithium bromide + sodium lactate) system, etc. Till now, people are still seeking an optimal mixed desiccant and mix ratio with relatively lower surface vapour pressure and cost effectiveness.

Besides, Park et al. [13] attempted to lower the vapour surface pressure of the liquid desiccant by adding four eight-carbon alcohol additives such as noctanol, 2-octanol, and 3-octanol.

The corrosion effects on the operating components of the systems should also be taken into account, the normal anti-corrosion methods mentioned in the open literature is adding additives to the liquid desiccant, or choosing parts made of synthetic plastic for the system, which can simultaneously lower cost compared with metal parts.

3.2. *Selection of packing materials*

The air dehumidification is generally effected by sprinkling the liquid desiccant from the top of the packing materials and bringing it in contact with the inlet process air. Packing materials is the place where mass transfer occurs between falling film of the liquid desiccant and inlet air. Hence, the selection of packing materials will undoubtedly exert influence upon the performance of the dehumidification unit.

Packing materials can be categorized as random packing materials and structured packing materials, the former are materials without regular geometric forms and placed randomly in the packing tower, and opposite structured packing materials, which has fixed geometric form. Pall ring, rosette ring, ladder ring, etc. are among the widely used random packing materials in gas–liquid contacting industrial equipments, such as cooling towers. Fig. 2. shows the two different kinds of packing materials.

Viewed from the perspective of fluid dynamics, the random placement of packing materials makes them inadaptable to the increase of liquid desiccant load, and results in the undesirable distribution of the desiccant over the surface of the packing materials. Furthermore, wall flow and channel flow may occur when the liquid-desiccant load is

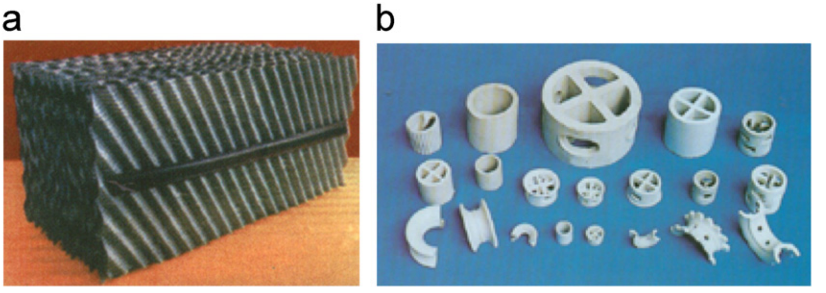

Fig. 2. Packing materials: (a) structured packing materials and (b) random packing materials.

small, and their enlargement effect is more serious compared with structured packing materials. The structured packing materials, by contrast, deciding the flowing direction of the liquid desiccant owing to their structured geometric patterns, are to some extent beneficial to the expansion of air-desiccant contacting area and meanwhile lower the liquid-desiccant resistance. Wavy plate packing materials, grid packing materials, and silk net packing materials belong to structured packing materials. Silk net packing materials own many advantages, such as high liquid gas separation rate, low-pressure drop, and flexible manipulation; however, they are vulnerable to corrosion and their channels are easily clogged. Therefore, considering the fact that the possible crystallization of the liquid-desiccant solution may clog the channel, the currently technically mature wavy packing materials are a better alternative.

The irrigated pressure drop is one of the major criteria for choosing packing materials for liquid-desiccant system, since the pressure drop is closely connected with the energy required by the fan for blowing the inlet process air. Gandhidasan et al. [14] provided a rigorous model for predicting the irrigated pressure drop in both structured and random packing materials, and his study revealed that the former outweigh the latter in terms of pressure drop for desiccant dehumidification systems. He also found the packing materials that provide the least irrigated pressure drop, both among structured ones and random ones.

In addition, for the random packing materials, Lazzarin et al. [15] found the way in which packing materials are piled in the dehumidifier will also exert an influence on the pressure drop and the performance of the dehumidifier.

Many researchers [16,17] conducted comparative experiments on random and structured packing materials. It is further identified that the structured packing materials bear the characteristics of high efficiency and high capacity for mass and heat transfer, and demonstrate good performance characteristics with a slightly low-pressure drop to mass and heat transfer coefficient ratio, as revealed in [18,19].

The air-desiccant contacting area, usually estimated and evaluated by volumetric area (the area per unit volume of the packing materials), void ratio (the void volume per unit volume of the packing materials), along with spacing intervals of packing material layers, are the major factors for design and selection purposes. Packing materials usually take the form of adjacent metal plates with small spacing intervals [39,42], or rolling felt with certain intervals in current studies, later, in order to enlarge the contacting area and thus improve the dehumidification efficiency, packings consisting of compact adjacent wavy packing layers with larger volumetric area such as comb paper [38] come into wide spread

use in related research. The void ratio can be used to measure the air flow resistance, which decreases with the increase of void ratio. Spacing interval between the layers is equally important, an optimum spacing interval will impose less resistance on the inlet air while improving the coverage ratio of the sprinkled desiccant on the packing material. As a result, if the intervals are unsuitably small or big, they will have an adverse impact on mass transfer ratio. The range of spacing intervals, 6–8 mm, is taken by the researchers in the open literature, and is proved to be suitable.

Furthermore, the equivalent diameter is also an important parameter for the preliminary prediction for heat and mass transfer occurring within packing materials. Al-Farayadhi et al. [20] defined the equivalent diameter of the structured packing materials with different cross sections of the flow channel by taking the arithmetic average of hydraulic radius of different flow sections.

The effective interfacial area of packing materials, namely, the wetting ratio of the packing sheets by the spraying desiccant solution is also an essential factor for the appraisal of packing materials' performance on mass and heat transfer. The wetting ratio of different packing materials differs from each other because of their separate cross sections and flow channels and surface characteristics. Shi et al. [21] found the correlation for mass transfer coefficient based on the physical principles of effective mass transfer area in a packing column. Gandhidasan [22] presented the comparison of the current available three models for the calculation of effective interfacial area of packing materials.

Besides, height and length of the packing material are also indispensable controlling parameter for designing purpose of dehumidification system. Apart from the selections of packing materials in terms of mass transfer ratio, the criteria for the quality of the packing material should also be noticed. First, the packing material should not be distorted if soaked in the liquid desiccant for a long time. Second, the packing material layers should not be bent under the acceptable inlet air velocity.

4. Liquid-desiccant dehumidification techniques and their applications

4.1. Flow patterns

There are generally three flow patterns for the dehumidifier, namely parallel flow, counter flow, and cross flow, as are shown in Fig. 3.

There are generally three models for analysis on dehumidification process, namely, finite difference model (Gandhidasan et al. [23,24], Factor and Grossman [25], Oberg and Goswami [26]), effectiveness NTU model (Stevens et al. [27]; Sadasivam and Balakrishnan [28]; Khan and Sulsona [29]), and model based on fitted algebraic equations (Khan and Ball [30]; Khan [31]). Among those models, the finite difference model can provide the most accurate performance analysis of the system with the equal basic equations.

Rahamah et al. [32] gave the theoretical analysis for parallel flow liquid-desiccant dehumidification based on control volume approach. Their analysis shows that low air flow rate and increased channel height produce better dehumidification and cooling processes. Low air flow rate will increase the contacting time between air and desiccant thus improves mass transfer; however, a certain minimum flow rate of the liquid is needed for the normal function dehumidifier. Increasing channel height will enlarge the contacting area between air and desiccant, which also enhances mass transfer. Rahamah et al. [33] analysed the parallel flow channel between air and solution film in a fin-tube arrangement.

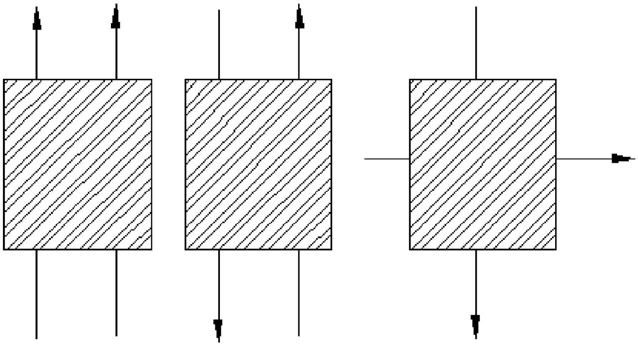

Fig. 3. Three main employed flow configurations for dehumidifiers.

They performed a parametric study to investigate the effects of different controlling parameters.

Counter flow is the most widely used flow pattern for design purposes of dehumidifier, and many related studies have been made upon it. Factor and Grossman [34] provided the experimental analysis concerning the packed bed absorbent dehumidifier. Gandhidasan et al. [35] offer the analysis of mass and heat transfer in a desiccant-air packed tower of counter flow configuration. Elsayed et al. [36] numerically explored the heat and mass transfer between calcium chloride solution and air in counter-flow packed bed arrangement; they offered the chart which will give a prediction of the exit air humidity and temperature. Lazzarin [37] carried out a study using calcium chloride and bromide chloride respectively as the liquid desiccants to determine the optimum operation for the packed tower and the regenerator.

Few related studies in the open literature carried investigations into the cross flow configuration for liquid-desiccant dehumidification systems. Thermal parameters of both liquid desiccant and inlet air, such as temperature and humidity ratio, change along horizontally and vertically. Dai and Zhang [38] developed the mathematical model of the cross flow liquid-desiccant dehumidification system with employment of honey comb paper as the packing material and analysed the Nusselt and Sherwood numbers at the liquid–air interface. Ali et al. [39] investigated the effects of addition of Cu-ultra fine particles in enhancing mass and heat transfer in a cross flow configuration of air and falling solution film. The addition of Cu-ultra fine particles also helps to stabilize the solution and enhance thermal and mass transfer between liquid desiccant and air. Liu et al. [40] carried a deep investigation into the heat and mass transfer occurring in the dehumidifier and provided the distribution of air humidity and temperature within the corrugated honeycomb paper packing materials with cross flow channels for process air and desiccant solution, they also analysed the distribution of concentration of desiccant solution in the packing materials.

Yoon et al. [41] numerical analysis on mass and heat transfer between process air and desiccant solution in a inner water cooled consecutive spaced plates with a cross flow configuration reveals the change of process air humidity and temperature along the plate, as well as the distribution of the concentration of the desiccant solution along the plate.

4.2. Dehumidifiers

The adiabatic dehumidifiers can be found in a wide range of industrial and residential applications, it can afford large air-desiccant contacting area with relatively simple geometry configuration, besides, its mass and heat transfer efficiency is high; however, it has the potential drawback of imposing a large pressure drop on process air when it flows through the packing materials, and the increase in temperature of liquid desiccant during the moisture removal process will exert an adverse impact on the performance of dehumidifier, which in turn make both humidity and temperature control of the process air less accurate. As the result, the inner cooled dehumidifier using cooling coils to remove the heat generated from dehumidification can be a sound alternative. The original inner cooled dehumidifier likes the one in Fig. 4.

It is obvious in Fig. 4 that the cooling coils embedded in the packing material serves to remove the heat from the course of dehumidification, the outer insulation layer here prevents the heat transference from the ambient air to the inner dehumidifier. However, the embedding of the cooling coils into the packing materials makes the installation more difficult. Besides, this type of dehumidifier should be equipped with insulation layer avoiding the adverse heat transfer from ambient air. The mass flow rate of desiccant solution is large for this kind of conventional dehumidifier to realize the optimal control of humidity. Fig. 4 demonstrates a cross flow configuration of air and solution flow for packing materials, which can be replaced by parallel and counter flow configurations. As Fig. 5 shows, the cooling coil can be laid in the layers to serve the same purpose of counteracting the heat from the moisture removal process, the consecutive plates here can be replaced by corrugated plates to enlarge the air-desiccant contacting area and thus enhance dehumidification. The plates here should be customized and increase the cost of the initial investment. The dehumidifier with one channel flowing air and desiccant solution and another channel flowing cooling air or cooling water from the evaporation cooler could also be a sound alternative. Just as Fig. 5 shows, Yoon et al.'s [41] dehumidifier in their study is just one of this kind.

There is also another type of inner cooled dehumidifier as is demonstrated in Fig. 6, the cooling coil replace the packing material serving as the air-desiccant contacting surface for mass and heat transfer, the finned tube is usually adopted in this kind of dehumidifier to enlarge the air-desiccant contacting area. Besides, the vertical distance and horizontal distance of the tubes should be considered for optimum mass and heat transfer. As the salt-desiccant solution is corrosive, the finned tubes here should be made of

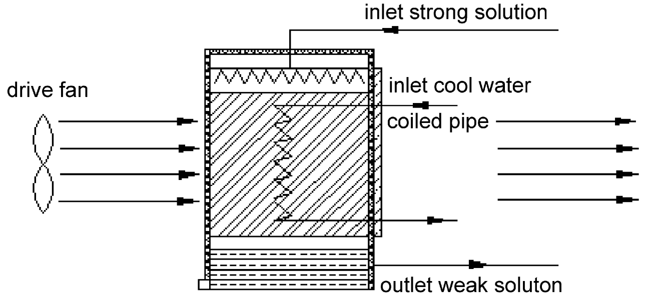

Fig. 4. Schematic diagram of the inner cooled dehumidifier.

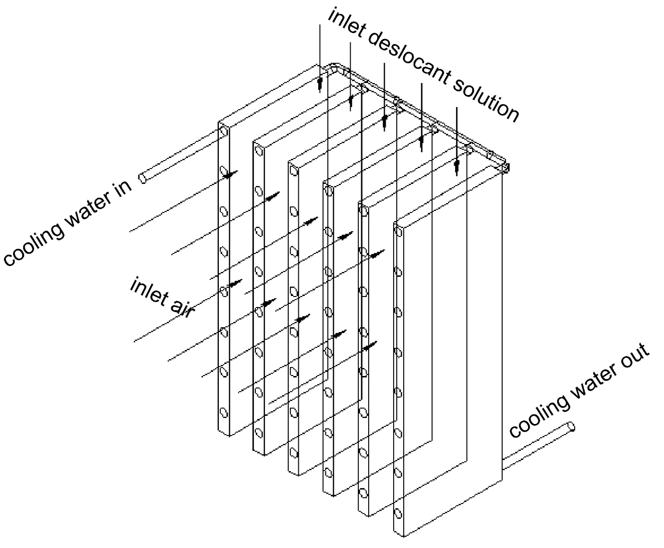

Fig. 5. Inner cooled dehumidifier with spaced parallel plate as packing materials.

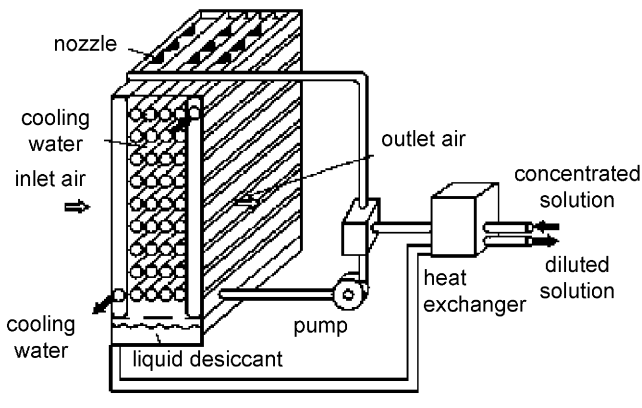

Fig. 6. Schematic diagram of other type inner cooled dehumidifier.

special anti-corrosion materials or high thermal conductivity metal of anti-corrosion coated layers.

Khan and Sulsona [29] chose the apparatus like Fig. 6 except that the cooling water is replaced by refrigerant in their hybrid system to realize the dehumidification of the process air and gave the profiles of humidity and temperature of the process air, the concentration and temperature of the desiccant solution, as well as the quality of refrigerant in the cooling coil.

Another new type of dehumidifier proposed by Saman and Alizadeh [42] can be seen as the derivative of the inner cooled dehumidifier, it make full use of the principle of direct evaporative cooling in one channel (secondary air stream is brought in contact with water spray counter currently) to cool the solution film flowing in anther channel (primary air

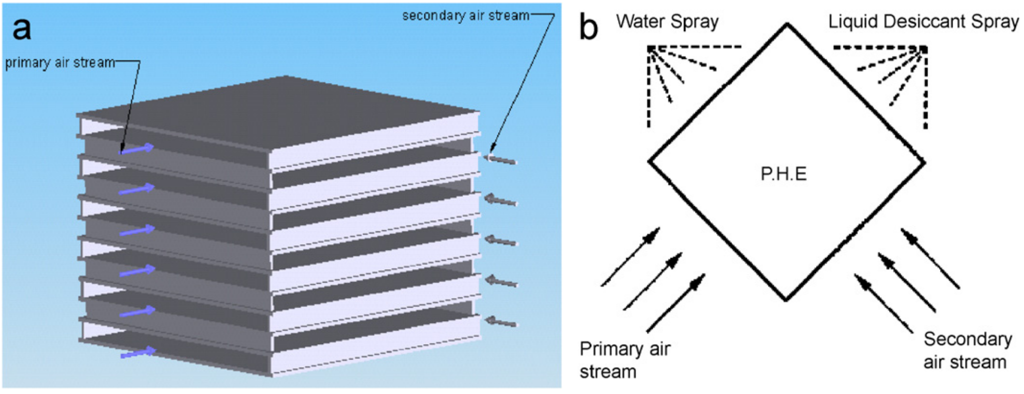

Fig. 7. Cross flow inner cooled dehumidifier: (a) schematic diagram of air flow directions and (b) fluid sprays contacting with different air streams.

stream is brought in contact with liquid-desiccant spray counter currently). Fig. 7 demonstrates this kind of dehumidifier.

4.3. Performance index

The moisture removal rate is an important parameter for measuring the thermal performance of the dehumidifier in terms of handling the latent heat load of process air:

$$\Delta d = d_{in} - d_{out}. \tag{1}$$

The dehumidification efficiency is in fact a dimensionless humidity ratio or vapour pressure ratio which can give a preliminary prediction of the dehumidification performance. Dai and Zhang [38] and Gandhidasan [43] have mentioned this definition in their studies which can be written as the follow equations:

$$\varepsilon_{de} = \frac{d_i - d_{out}}{d_i - d_{equ}}. \tag{2}$$

d_{equ} is the humidity of the air which is in vapour pressure equilibrium with the desiccant solution. Here d_{equ} is decided by the surface pressure of the inlet desiccant solution, which is the assumed optimum humidity the exit air could reach.

The dimensionless humidity ratio and pressure ratio provide the criterion to measure the extent to which the dehumidification process approaches the assumed optimum one. The moisture removal rate and dehumidification should be combined to give a more accurate appraisal of the overall performance of the dehumidifier.

Additionally, the cooling effect on the air is also involved in the dehumidification process if the inlet air temperature is higher than that of the desiccant solution. Gandhidasan [43] defined the dimensionless temperature ratio in his study, which in accordance with the previously defined humidity dimensionless ratio in terms of the form:

$$\eta = \frac{t_{a,in} - t_{a,out}}{t_{a,in} - t_{s,in}}. \tag{3}$$

The above-mentioned two dimensionless ratios, coupled with the related energy balance equations can be used to predict the mass removal rate of the moisture with the known initial conditions of air and desiccant solution.

4.4. Analysis

The vapour pressure of the process air is the function of humidity ratio and is not affected by the temperature. The surface vapour pressure of the desiccant solution is the function of the concentration and temperature of the desiccant solution. There are many parameters that have effects on the dehumidification performance, for example, the inlet air temperature, the humidity, the air mass flow rate, the desiccant solution mass flow rate, the solution temperature and concentration, the dimensions of the packing materials, etc. The performance optimization generally should be balanced between such parameters.

MR (air to solution mass ratio) is also an essential parameter for both optimization and comprehensive analysis [44] of both dehumidification and energy storage in the whole system. Zhao and Shi [44] provided the criterion for optimization of MR for two different dehumidifiers, namely, adiabatic dehumidifier and inner cooled dehumidifier, which is based on the principle of energy conversation and the demand for energy storage during the dehumidification process. Li et al. [45] analysed the operating performance of different mass flow ratios between desiccant solution and process air under the theoretical reversible conditions of dehumidification process. The mass flow ratio should be seriously considered for the optimum operation of the system, if the mass flow rate of the desiccant solution is too small, an even spread of desiccant solution over the packing layer will not be ensured, while if the mass flow rate of the desiccant solution is too large, the inlet and outlet concentration difference of desiccant solution will be small, which make regeneration of the weak solution more difficult and entail more energy for pumping desiccant solution.

Besides, there are other major impacting parameters based on different theoretical analysis model. For effective NTU model, the NTU should be considered as a primary impacting factor, Stevens et al. [27] made analysis in his study.

Nusselt number and Sherwood number are two dimensionless parameters relating to mass transfer occurring between two different substances, and Reynolds number is an important thermodynamic parameter for fluids. Ali et al. [39] carried out an investigation into the relationships among these dimensionless numbers.

4.5. Multi-stage liquid-desiccant dehumidification

Although the desiccant solution is cooled before it is pumped into the packing materials, but with proceeding of the moisture removal process, the increase in the temperature of desiccant solution is inevitable. For single-stage dehumidification, an adverse temperature increase in desiccant solution, which will lower the driving force for mass transfer between desiccant solution and process air, will be caused.

The concept of multi-stage dehumidification was studied by Jiang et al. [46]. Fig. 8 demonstrates the multi-stage dehumidifier, which introduced an original dehumidifier by installing several single dehumidifier modules in series, in which the liquid desiccant flows from module to module and is separately cooled in every single dehumidifier module to better dehumidification. This new mode of dehumidification overcomes the potential disadvantage in the conventional single-stage dehumidification.

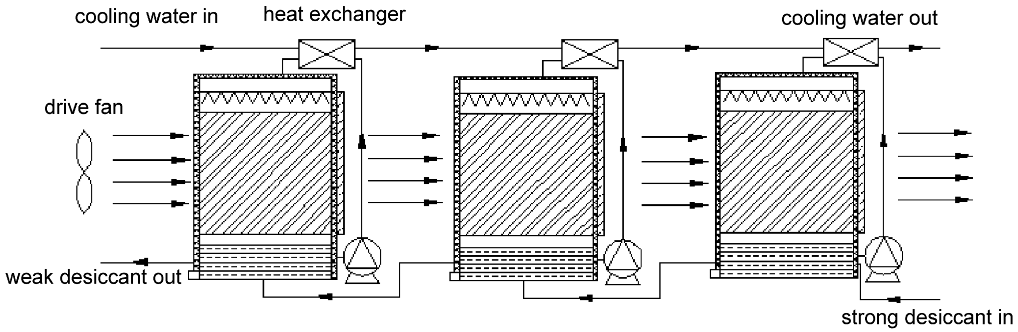

Fig. 8. Schematic diagram of the multi-stage dehumidifier.

As is demonstrated in Fig. 8, the inlet air first treated by the weakest desiccant solution, because weak desiccant solution has the highest surface vapour pressure, and the inlet air also owns the highest vapour pressure. Then, the process air is dried, and its vapour pressure is decreased. In the last module of the dehumidifier, the strongest solution with the lowest surface vapour treats the air with lowest vapour pressure. As a result, the vapour pressure difference between desiccant solution and process air is kept at a moderate level without drastic change. While for the conventional dehumidifier, the vapour pressure difference is decreased with the proceeding of the moisture removal process. The irreversible loss in multi-stage dehumidifier is greatly lowered compared with that of conventional dehumidifier. The demand for mass flux of the desiccant solution for conventional dehumidifier is great to realize the dehumidification requirements, as a result, the inlet and outlet concentration difference of the desiccant is small, thus the vapour pressure difference between desiccant solution the process air is increased, consequently, the irreversible loss is enhanced, which eventually contribute to the aggravating of the system performance.

As for the multi-stage dehumidifier, the mass flow rate of desiccant solution in each module is small, but the mass flow rate of it for all modules is relatively large, thus the inlet and outlet concentration difference of the desiccant solution is increased, which will effectively reduce the irreversible loss and facilitate the effective execution of the regeneration of the weak desiccant solution; meanwhile, the separate cooling of inlet desiccant solution will serve the same purpose.

However, the relatively small mass flow rate of the desiccant solution may impose a bad influence on the even spread of it over the packing layer, which will greatly aggravate the mass transfer process, so the spray tube of the desiccant solution should be specially devised to facilitate the even distribution of the desiccant solution. The comparative analysis [47] on the irreversible loss of multi-stage dehumidifier and conventional dehumidifier during dehumidification process is shown in Fig. 9.

5. Regenerators

As the weak desiccant solution flowing from the dehumidifier should be concentrated to an acceptable level to maintain its capacity for dehumidification, the regenerator is an indispensable constituting part for the whole liquid-desiccant dehumidification system.

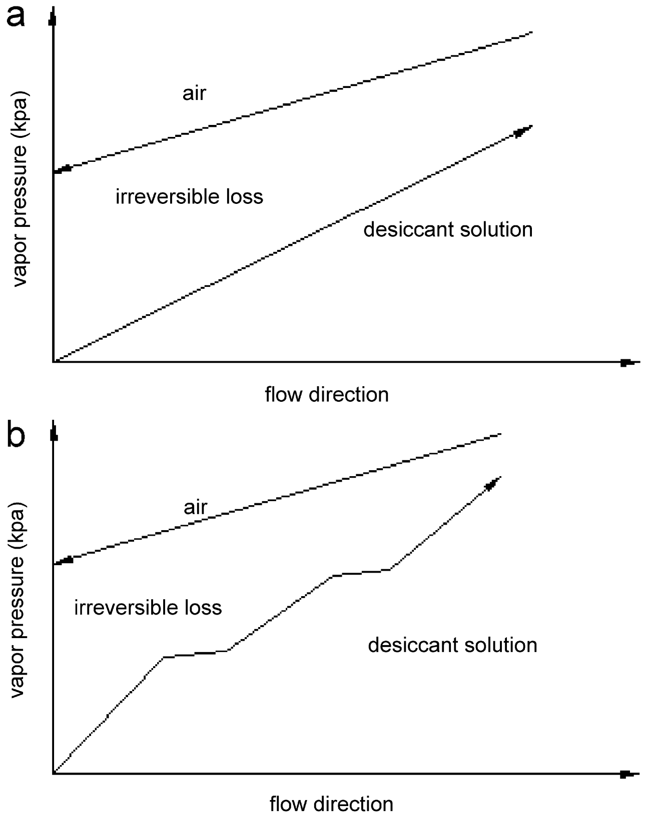

Fig. 9. Irreversible loss comparison between the multi-stage dehumidifier and conventional dehumidifier: (a) irreversible loss for conventional dehumidifier and (b) irreversible loss for multi-stage dehumidifier.

Generally, the low-grade energy, such as solar energy, waste heat, and hot water discharged from factories, is considered as an advisable and convenient alternative.

The regenerator can be the same as the dehumidifier in terms of configuration and packing materials, however, the processes occurring within them are just opposite. The weak desiccant solution is generally heated to the optimum regeneration temperature before it flows into the regenerator. A heat exchanger between weak desiccant solution flowing out of the dehumidifier and strong solution flowing into the regenerator is necessary. Moreover, an ancillary heater is needed if the low-grade heat source cannot afford the consumption needed for regeneration.

5.1. Performance evaluation

There is no doubt that the concentration of outlet desiccant solution is an essential criterion for assessing the performance of the regenerator, whether this concentration approaches that of the initial solution flowing into the dehumidifier is the core of this issue. As a result, a parameter is needed to measure the extent to which the weak solution is regenerated. Here the dimensionless regeneration efficiency is given by Gandhidasan [48]

as follows:

$$\varepsilon_{re} = \frac{d_{a,out} - d_{a,in}}{d_{a,out,max} - d_{a,in}}. \tag{4}$$

$d_{a,out,max}$ is decided by the inlet conditions of weak desiccant solution, which sets the maximum humidity ratio that the outlet air from regenerator could reach.

The above equations for regeneration efficiency are defined from the perspective of the air stream flowing through the regenerator.

Here, another version viewed from desiccant solution's perspective is given as follows [49]:

$$\varepsilon_{re} = \frac{c_{s,out} - c_{s,in}}{c_{s,sat} - c_{s,in}}. \tag{5}$$

The desiccant solution's concentration at the saturation point under the average regeneration temperature is ceiling line for the concentration of regenerated solution.

c_{sat} is the concentration of the saturated desiccant solution at the given average regeneration temperature, which should be higher than the initial concentration of the desiccant solution flowing into the dehumidifier at the appropriate range of regeneration temperature.

5.2. Configurations of different solar collector regenerators

The solar collector has been widely used for regeneration purpose in liquid-desiccant dehumidification system, for the solar energy is readily available, especially when energy shortage has become an issue of wide concern around the world. The concept of the system was first proposed in the USSR by Kakabaev et al. [50] in 1969. The solar collector can be used directly and indirectly for regeneration. In the former mode, the heat-collecting fluid is the weak desiccant flowing from the dehumidifier. In the latter mode, the heat-collecting fluid in the solar collector is water, which is then used to preheat the weak desiccant solution flowing into the regenerator. The former is more effective in terms of solar energy utilization ratio, for the regeneration temperature is more or less equal to that of solar collector plate, besides, the regeneration chamber is eliminated. However, when the solar insolation is not ideal in overcast days, the solar collector itself cannot handle the regeneration of desiccant solution; as a result, auxiliary heaters should be equipped with the solar collector regenerators to heat the weak solution flowing into the solar collector to achieve the better performance of regeneration.

The solar collector regenerators can be divided in different categories as follows: (1) open-type; (2) closed-type; (3) natural convection; and (4) forced convection. Among all those categories, the forced convection solar collector regenerator is presently proved to be the most effective and is widely used.

5.2.1. Open-type

The open-type solar regenerator is one of the simplest systems for concentrating the weak desiccant solution. It consists of a distributor, a tilt blackened surface, and an insulator layer at the bottom of the solar collector. It is shown schematically in Fig. 10. The weak desiccant solution flows over the surface of the solar collector and is brought in contact with the ambient air, because the surface vapour pressure of the desiccant solution

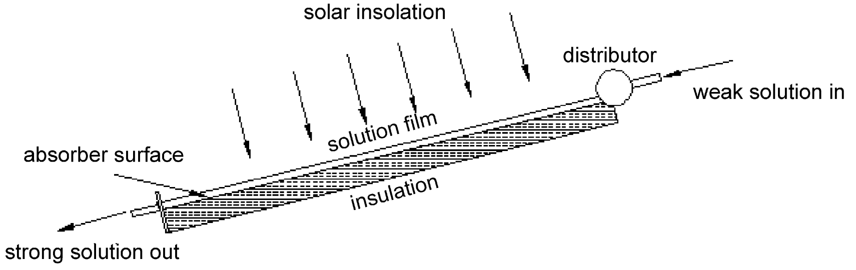

Fig. 10. Schematic diagram of open-cycle solar collector regenerator.

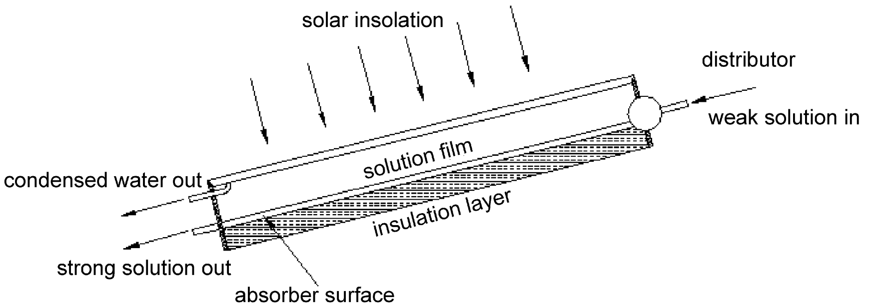

Fig. 11. Schematic diagram of close-cycle solar collector regenerator.

exceeds that of the ambient air, so mass transfer occurs, and the concomitant heat transfer takes place in the form of convection, radiation and conduction in addition to evaporation.

Kakabaev et al. [51,52] reported their 4-year experimental results on an open-cycle solar air-conditioning pilot plant, and proposed the related operational and structural improvement on the system operating under summer conditions. Collier [53] developed the analytical procedures for calculating the mass rate of the water evaporated from the weak desiccant solution. Peng and Howell [54] provided a more accurate numerical method. Gandhidasan [55] derived a simple expression for the water evaporation rate from the weak desiccant solution. Kumar and Devotta [56] presented a time-dependant heat and mass transfer numerical analysis on an open-cycle solar collector regenerator. Yang and Yan [57] performed a computer simulation study for an open-cycle absorption solar cooling system and validated the system's feasibility in humid climate conditions.

However, the system is strongly dependant on the weather conditions; hence, adverse climate conditions such as gales and rains will destroy its performance. Because of its open cycle, the energy loss of the desiccant to the ambient air will decrease the regeneration temperature.

5.2.2. *Close-type*

Close-type solar collector regenerators can avoid the adverse influence of the surrounding atmosphere and contamination of dust. The close-type solar collector regenerator likes the open-type ones covered will a single layer of glass, and both ends of the regenerator are closed. The regeneration process taking place within it is similar to that of solar still. The solar insolation energy is intercepted by the falling film of desiccant

solution, then the water evaporating from the solution rise to the underside of the upper glazing by convection where it is condensed and flows along the surface of glass to condensed water tank. The energy transfer taking place with the regenerator is in three forms, namely, radiation, convection, and evaporation-condensation. The bottom of the solar collector plate must be well insulated to avoid energy loss. The schematic diagram of the closed type solar collector regenerator is demonstrated in Fig. 11.

A theoretical investigation of titled solar still as the regenerator for weak desiccant solution was carried out by Gandhidasan [58]. Although the close-cycle solar collector regenerator can effectively lower the energy loss caused by convection, the lack of ventilation will lower that driving force for regeneration, namely, the vapour pressure difference between the air and the solution film, because the limited vapour condensation on the underside of the glazing layer will inevitably contribute to the increase of the vapour pressure of the air in the regenerator.

5.2.3. *Solar collector regenerator with natural convection and forced convection*

The solar regenerator with convection is somewhat similar to the closed-type solar collector regenerator except that the ends of it was opened for ventilation, either forced flow wind or natural flow wind. The schematic diagram of the wind flow solar collector regenerator is shown in Fig. 12.

For natural convection solar collector regenerator, the inlet conditions of desiccant solution and glazing height are controllable, while for forced convection solar collector regenerator, the mass flow rate of the inlet air is also controllable. For natural convection solar collector, the length of the absorption plate is limited by the randomness of the wind flow direction, which will create stagnant air pocket in the solution film to reduce the effectiveness of the solar regenerator. Kakabaev et al. [59] found that the mass transfer coefficient and exit solution temperature increased linearly with solar insolation. McCormick et al. [60] reported that if the height of the glazing exceeds a certain value, its performance resembles that of unglazed solar collector regenerator except that the improvement on low irradiance levels and a reduced sensitivity to wind speed. Nelson and Wood [61] explored and established the evaporation rate model for a natural convection glazed collector/regenerator and made a comparative study on the performance of it and unglazed solar collector regenerator.

For forced convection solar collector regenerator, the continuous air flow can be ensured in the regenerator and the flow in the air channel can be maintained laminar, thus

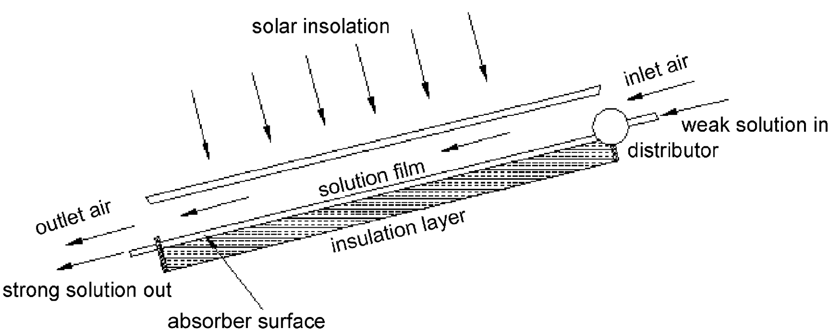

Fig. 12. Schematic diagram of convection solar collector regenerator.

the pressure drop is not excessive. The forced convection solar collector regenerator can be classified as forced convection parallel solar collector regenerator and forced convection counter ones viewing from the inlet air flow direction. According to previous studies, the parallel flow seems to be more effective in mass transfer (Saman et al. [62]; Ji and Wood [63]). Yang and Wang [64] investigated the optimum glazing height for a glazed solar collector regenerator, they found that the optimum glazing height is 0.07 m for a glazed solar collector regenerator, and an optimally glazed solar collector regenerator gives a better performance than an open type system. Ji and Wood [63] indicated that the mass transfer is enhanced with the increase of inlet air and solution temperature and is the inverse function of solution mass flux. A relatively large air mass flow rate could also contribute to the improvement of regenerator performance. Yang and Wang [65] made experimental studies on forced convection solar collector regenerator, the influence of the individual controlling parameters are analysed, besides, a comparative study was made with the natural convection solar collector regenerator. Alizadeh and Sama [66] carried out experimental studies on the forced parallel flow solar collector regenerator, and found that a optimum air to solution mass flow rate exists for the maximum water evaporation rate under the given operating conditions and climate conditions.

5.2.4. The indirect use of solar energy for regeneration purpose

Solar energy can also be employed indirectly to regenerate weak solution from the dehumidifier. As Fig. 13 shows, heated water flowing from solar collector are used to pre-heat the weak solution before it flows into the regenerator. However, for this kind of regenerator, heat exchanger accounts for more energy loss due to its limited heat

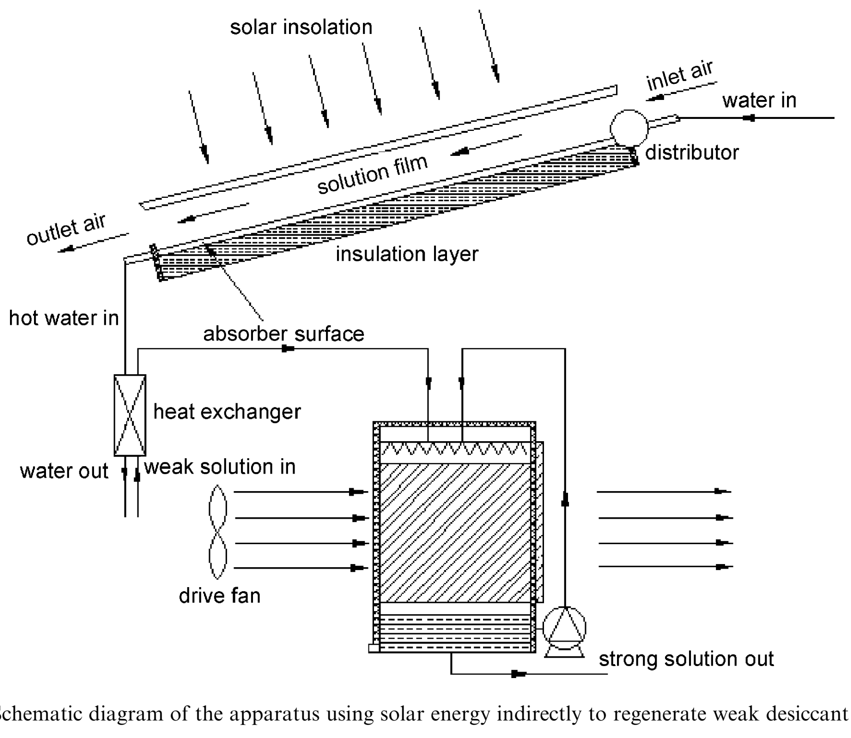

Fig. 13. Schematic diagram of the apparatus using solar energy indirectly to regenerate weak desiccant solution.

exchanging effectiveness. It is perhaps that the overall performance of this mode of regeneration is better than that of solar collector regenerator; however, its solar energy utilization is not that ideal compared with the direct solar collector regenerator.

5.2.5. The multi-stage regenerator

Although the collector's simple configuration and the ready availability of the solar energy make it come into widespread use in absorption solar cooling systems as the regenerator; however, it has the drawback in achieving balanced mass transfer along the flowing direction of desiccant solution. It is obvious that the desiccant solution gets concentrated along the collector plate, but the high concentration of the solution makes it more difficult to be regenerated because of the reduced vapour pressure difference between the solution film and the air. The multi-stage regenerator can get a relatively balanced mass transfer performance by using the high-temperature heat source to heat the slightly strong solution and low-temperature heat source to treat the weak solution. A high-energy utilization ratio can be achieved by doing so. The schematic diagram of it is shown in Fig. 14.

The multi-stage regenerator can be combined with solar collector regenerator which provides the inlet hot water, the low-grade energy source, such as water heat and gas could also act as the heating source for the hot water.

5.2.6. The novel two-stage regenerator

Inspired by the absorption cooling system, Lowenstein et al. [67] presented a brand new regenerator consisting of high-pressure generator and low-pressure generator, as well as several heat exchangers. The schematic diagram of this novel regenerator is shown in Fig. 15.

The hot water vapour evaporated from the high-pressure regenerator are employed to heat the weak solution in low-pressure generator, the low-pressure generator is evacuated before operation to maintain a relatively low temperature. The heat exchangers in this diagram are used to pre-heat the inlet weak solution to achieve a better regeneration performance. The heat exchangers here also serve the purpose of heat recovery from the hot water vapour before it is discharged into the ambient surroundings, and therefore lessen the heat pollution caused by water vapour. The regenerator is driven by low-grade energy and is less dependant on ambient climatic conditions compared with the conventional regenerators functioning primarily by the fed air stream. The creative

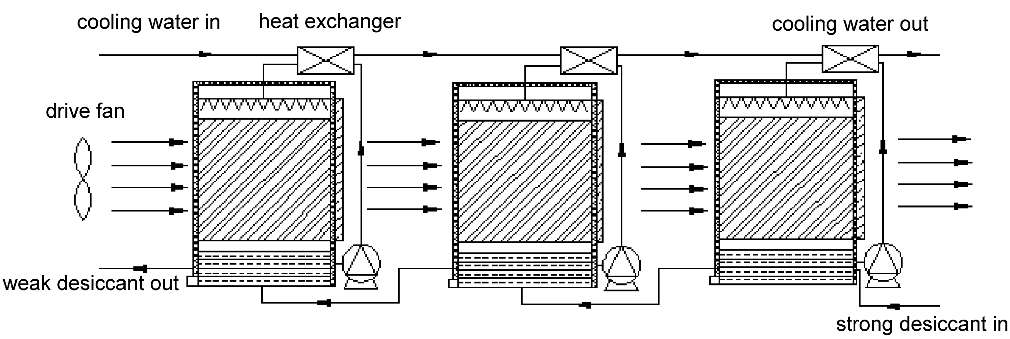

Fig. 14. Schematic diagram of multi-stage regenerator.

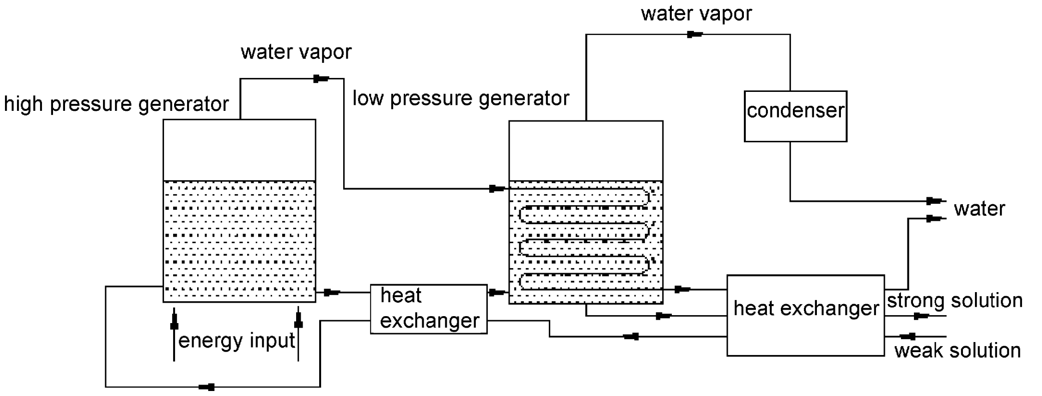

Fig. 15. Schematic diagram of a novel two-stage regenerator.

feature of this regenerator is that the high driving force for mass transfer exists in the low-pressure generator, which is evacuated before put into operation. However, precautions should be taken to prevent leakage in low-pressure generator. High-pressure generator is the only energy consumption component of this regeneration system, which could also be driven by low-grade energy.

5.3. Energy storage

Energy storage can also be realized by strong desiccant solution, which stores the ability of dehumidification at the expense of certain amount of energy (energy for regenerating the weak solution) rather than the quantity of heat. Energy could be stored easily and is non-dissipative in the form of latent heat in desiccant solution. Kessling et al. [68] carried experimental studies on the relationships between dehumidification enthalpy storage and different impacting factors in a cooled absorber under ARI outdoor conditions.

The energy storage capacity by desiccant solution can be defined as the following equation [69]:

$$S = \frac{(m_{a,in}d_{a,in} - m_{a,out}d_{a,out})\rho_{s,out}r}{m_{s,out}}, \tag{6}$$

r is the latent heat of vapourization at the average temperature of desiccant solution in the dehumidifier. The above equation shows that heat storage capacity is dependant on the moisture removed from air in dehumidifier. As a result, the energy storage capacity range of the regenerated strong desiccant solution is limited, because this equation indicates that the mass rate of moisture removed from desiccant during regeneration process equals that of the moisture condensed from the air during dehumidification process.

Energy storage by the desiccant solution in the liquid-desiccant dehumidification system is to some extent at the expense of energy, which will lower the coefficient of the system performance, besides, the highly concentrated solution is not conveniently stored for the crystallization occurs easily if the temperature of the solution decreases a little bit.

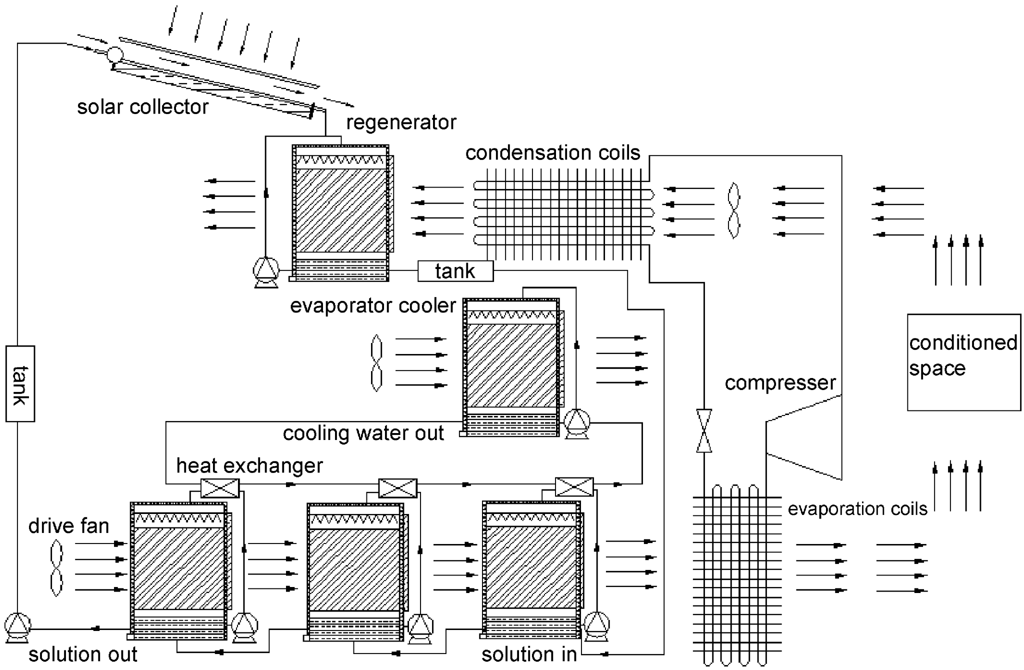

Fig. 16. Schematic diagram of VCS combined with liquid-desiccant dehumidification hybrid system.

Thus, the relationship between energy consumption and energy storage should be correctly handled.

6. Air-conditioning application

Liquid-desiccant dehumidifiers could be coupled with conventional vapour compression systems (VCS), vapour absorption systems (VAS) to realize the better manipulation of humidity and air for conditioned spaces, as well as greatly improving the performance of VCS and VAS systems. The VCS combined with liquid-desiccant dehumidification hybrid system is shown schematically in Fig. 16. The VAS combined liquid-desiccant dehumidification hybrid system is shown schematically in Fig. 17. Parsons et al. [70] found that the heat pump coupled with liquid-desiccant dehumidification system could achieve better capacity and improvement than the heat pump alone. Compared with the above-mentioned evaporation cooler in liquid-desiccant dehumidification and cooling systems, VCS and VAS is less affected by the ambient climate condition in handling the sensible cooling of the process air for conditioned spaces. However, VCS and VAS is less advantageous compared with evaporation coolers considering the cost. The addition of liquid-desiccant dehumidifier to the VCS and VAS systems could greatly alter the conditions flowing between the major components of VCS and VAS systems, thereby contributing to their energy savings and improvement of performance. Yadav and Kaushik [71] found the 35% energy saving could be obtained by adding a liquid-desiccant dehumidifier to a VCS cycle. Khalid Ahmed et al. [72] carried out a simulation on a hybrid system using LiBr as working fluid for the absorption and dehumidification, and they

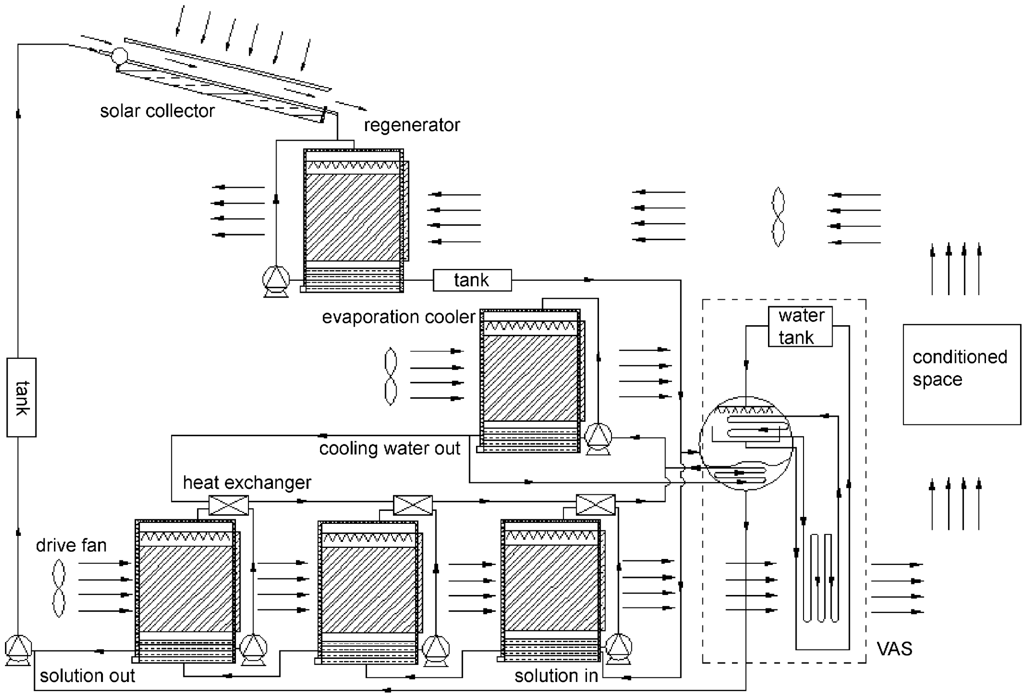

Fig. 17. Schematic diagram of VAS combined with liquid-desiccant dehumidification hybrid system.

found that the COP obtained in this hybrid system is around 50% higher than that of a conventional VAS system, additionally, low ambient water temperature and air humidity ratio will further improve the COP. Dai et al. [73] investigated the addition of the desiccant dehumidification and cooling cycle on the improvement of VCS's overall performance, they found the hybrid systems have the benefits of reduced electric power consumption, reduced size of VCS, and low mass rate of the condensed water because of the lower condensation temperature. They also studied the various individual parameters' influence on the hybrid system's COP, ECOP, and TCOP. Ania et al. [74] explored the height of the absorber a hybrid system consisting of a VCS, a liquid dehumidification system, and a solar collector regenerator for the optimum system overall performance. Yadav [75] carried out techno-economic and energy conversation studies on the hybrid systems. Sick and Bushulte [76] made the analysis of the seasonal performance of hybrid liquid-desiccant cooling systems.

Compared with the VCS hybrid system, the VAS hybrid system needs more working fluid for both subsystems of liquid-desiccant dehumidification and VAS, and the regeneration load for regenerator is much heavier. As a result, the higher preheating demand is set for solar collector to realize better performance of the regenerator. Besides, the return air from the conditioned space is not pre-heated before entering the regenerator compared with VCS hybrid system. However, the driving heat source could be the total solar energy or other thermal energy, with no consumption of electricity, which caters to the need of energy conservation and full utilization of natural and low-grade energy.

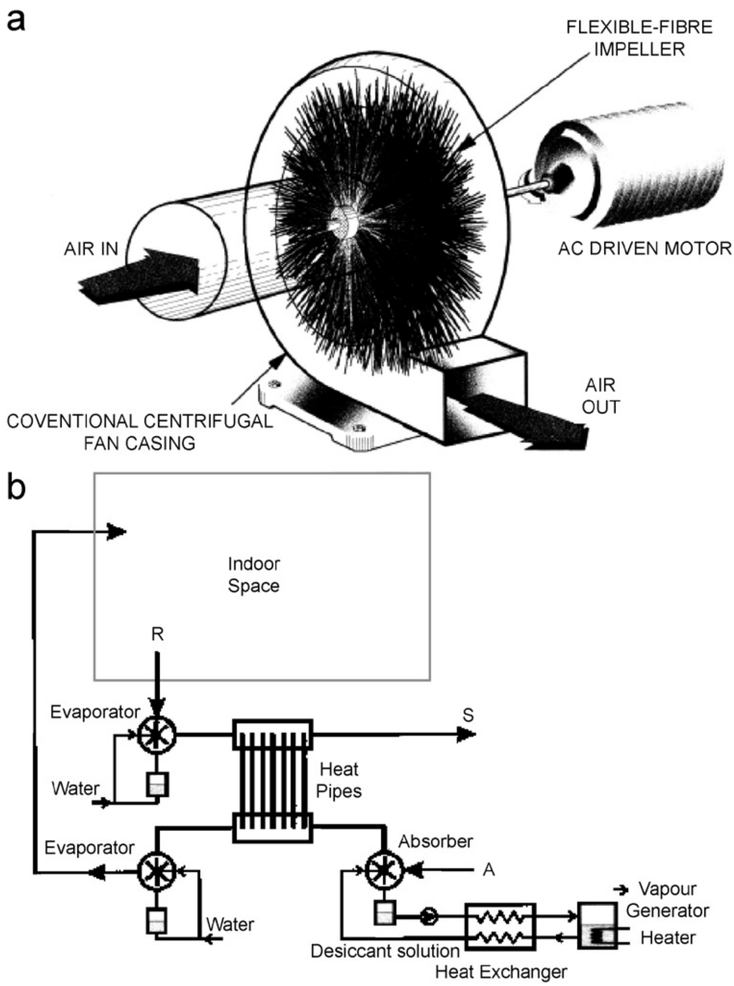

Fig. 18. A novel air-conditioning system using a liquid desiccant: (a) schematic diagram of dehumidifier and (b) schematic diagram of its related system.

Besides the above-mentioned two kinds of widely employed hybrid systems, liquid-desiccant dehumidification systems can be combined with heat pumps, and cooling, heating, electricity cogeneration systems to constitute the hybrid systems with better overall performance and more final products (desiccant dehumidification used in CHP or BCHP systems) than the single systems alone.

As is known to us all, evaporator and dehumidifier is the core component of liquid-desiccant dehumidification and cooling system. Efforts have made to come up with new types of them. Oliveira et al. [77] invented an original type of dehumidifier and made investigations into the related dehumidification systems.

This novel dehumidifier employs a modified chimney sweep brush consisting of fine nylon needles as the impeller in the centrifugal fan case, and the surface of the nylon needles function as the contacting surface between process air and desiccant solution when

they are wetted by the solution owing to the centrifugal force provided by the motor. Fig. 18(b) demonstrates the schematic diagram of its related system, and the heat pipes here serve to pre-cool the process air by the indoor return air. The evaporation cooler between conditioned space and heat pipes further cools the indoor return air, which help process air flowing through the heat pipes to achieve an optimal temperature for indoor comfort requirement.

7. Conclusions

Liquid-desiccant dehumidification techniques have made great strides in the past decades, and some are commercialized and employed to satisfy industrial and residential needs. Theoretical models about desiccant dehumidification have been established and insightful analysis has been performed. However, it is still uncertain about the exact process of mass and heat transfer, such as the absorption heat distribution between desiccant solution film and process air, wetting ratio of the desiccant solution over the packing sheets in dehumidifier, etc. Although liquid-desiccant dehumidification systems can easily realize the independent control and temperature and humidity ratio of the process air, but it has the potential drawback in big dimension and unstable operation, which hinder its widespread applications, besides, its continuous operation and performance is influenced by the climate conditions, since the performance of solar collector is decided partly by the ambient air conditions and solar insolation. Therefore, the system performance is slightly unstable compared with that of conventional air conditioning units. The emergence of hybrid systems will partly lessen the system's instability, besides, hybrid system's capacity for handling the sensible cooling of the process air far outweigh that of evaporation coolers, which is commonly employed by the conventional liquid-desiccant dehumidification and cooling systems. Furthermore, the evaporation cooler's performance is limited by the areas climate conditions. Above all, hybrid systems should be lied emphasis on to widen the use of desiccant dehumidification techniques for space conditioning. Also, further analytical and experimental investigations should be made to deepen the understanding of mass and heat transfer occurring within the dehumidifiers to improve the system's overall performance.

Acknowledgements

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